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ADHESION OF VARIOUS METALS TO A CLEAN IRON (011) SURFACE STUDIED WITH LEED AND AUGER EMISSION SPECTROSCOPY

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16. Abstract Adhesion experiments were conducted with various metal single crystals contacting a clean iron (011) surface. All the metals were examined in the clean state and some with oxygen present on their surface. Both LEED and Auger analyses were used to determine the nature of surface changes that took place as a result of adhesive contact. Adhesion to clean iron was observed with all metals and oxygen-covered metal surfaces. With clean metals the cohesively weaker transferred to the cohesively stronger. Chemical activity of the metal also influenced measured adhesive forces. When oxygen was present on the metal surface, adhesive forces could be related to chemical binding energy of the metal to oxygen.					
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ADHESION OF VARIOUS METALS TO A CLEAN IRON (011) SURFACE

STUDIED WITH LEED AND AUGER EMISSION SPECTROSCOPY

by Donald H. Buckley

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SUMMARY

Adhesion experiments were conducted with various metals contacting a clean iron (011) surface. The metals included copper, gold, silver, nickel, platinum, lead, tantalum, aluminum, and cobalt. Some of the metals were examined with oxygen present on their surface as well as in the clean state. LEED and Auger emission spectrometer analyses were used to determine the nature of surface changes that took place as a result of adhesive contact. Adhesive contact was made with a 3.0-millimeter-diameter flat of the nonferrous metal contacting a larger flat of the iron (011) surface at applied loads of 20 to 350 dynes (20 to 350×10^{-5} N). All experiments were conducted at 20° C and 10^{-10} torr.

The results of the investigation indicate that, with the various metals contacting iron, the cohesively weaker will adhere and transfer to the cohesively stronger. The chemical activity of the metal also exhibited an influence on adhesive forces measured. The more reactive metals gave higher adhesion values. With oxygen present on the metal surface, where the metal to oxygen chemical bond was weaker than the metal cohesive bonds, the adhesive forces measured could be correlated with the binding energy of the metal to oxygen.

INTRODUCTION

There are a number of fundamental properties of metals which relate to the adhesion behavior of metals in contact.

Crystal structure influences adhesion. Close packed hexagonal metals exhibit lower adhesion than do body- and face-centered cubic metals (refs. 1 to 3). This results from the minimum in cohesive energy between the basal planes of hexagonal metals (ref. 4).

The density of atomic planes in metals exerts an influence on adhesion. High-atomic-

density, low-surface-energy planes exhibit lower adhesive forces than do other planes (ref. 2). This relates to the fact that the greater the number of bonds formed by an atom with like atoms within a plane, the more stable is the resulting structure and the lower is the energy available for surface interactions with dissimilar or adatoms (ref. 5).

Attempts have been made to correlate bulk properties of metals such as solid solubility with adhesion (refs. 6 and 7). Care must be taken in the use of such correlations because a plane of metal atoms on the surface behaves differently than that same plane would in the bulk metal.

Ferrous base materials are the most widely used in lubrication mechanism design and in engineering practice. Frequently, in such devices, ferrous surfaces are contacted by nonferrous materials. The adhesion behavior of ferrous surfaces with nonferrous surfaces is therefore of practical as well as fundamental interest.

The objectives of this investigation were to determine (1) the nature of the adhesion of various nonferrous metals to iron, (2) the influence of oxygen on some nonferrous surfaces on adhesion to iron, and (3) the effect of solubility and chemical activity on adhesion of nonferrous metals to iron. Metals having body-centered, face-centered and hexagonal structures were examined in contact with iron. Adhesion experiments were conducted with high-atomic-density, low-surface-energy planes to minimize adhesive forces. All experiments were conducted at 10^{-10} torr and 20°C with a 3.0-millimeter-diameter nonferrous flat contacting an iron (011) surface under an applied load of 20 dynes (20×10^{-5} N). LEED (low energy electron diffraction) and Auger emission spectroscopy analyses were used to study the surface changes that took place as a result of adhesive contact.

APPARATUS

The apparatus used in these studies is shown schematically in figure 1. The single-crystal surface mounted in the center of the chamber could be rotated 360° . This rotatability allowed for Auger analysis and obtaining a LEED pattern of the crystal surface. The crystal could also be moved in the lateral and vertical directions, allowing for examination in the noncontact areas.

The crystal specimen was supported in the chamber by means of two metal rods (insulated) which were used to resistance heat the crystal. This was used for cleaning and the removal of trapped argon after ion bombardment. A 100-ampere alternating-current power supply was used for resistance heating. The single-crystal, flat-ended fiber specimen, which contacted the single-crystal iron (011) surface, was mounted in a stainless steel holder which was, in turn, mounted to a 1.5-millimeter-diameter stainless-steel beam. The beam was mounted in a bearing-containing yoke. At the end

of the beam beyond the pivot point, and opposite the smaller cylindrical specimen, was a small permanent magnet. Outside the chamber wall were two electromagnets. The permanent magnet and the electromagnets were positioned in such a manner as to have like poles facing each other. A variation in the current applied to the magnets could be used to move the beam.

The current applied to the electromagnets was calibrated in terms of the force applied in the adhesion experiments. Load applied to the surfaces in contact was measured, as was the force required to separate the crystal surfaces.

The basic LEED and Auger systems were obtained commercially. The LEED electron optics and the vacuum system were of the standard type used by those engaged in LEED studies. The Auger spectrometer gun was located at a position 90° from the LEED gun (see fig. 1). The electron analyzer was of the four-grid type. The LEED beam diameter was 0.6 millimeter. The vacuum system consisted of vacsorb pumps, an ion pump, and a sublimation pump. The system pressure was measured with a nude ion gage, and all experiments were conducted with the vacuum system in the range of pressures from 10^{-11} to 10^{-10} torr. No cryopumping was used.

EXPERIMENTAL PROCEDURE

All of the metals used in this study were of zone refined purity. The iron crystals were cut by electric discharge machining from a rod into specimens having a diameter of 8.0 millimeters and a length of 6.0 millimeters. The crystals were then taken down on metallurgical papers to 600 grit and then electropolished. The nonferrous single crystals were 3.0 millimeters in diameter and were 6.0 millimeters in length. The crystal orientations were checked after electropolishing, and the iron specimens were placed in a vacuum tube furnace. They were heated to 600°C and held under vacuum for 24 hours, at which time hydrogen gas was admitted. The system was then reevacuated. This procedure was repeated for a 2-week period. The purpose of heating was to attempt to drive carbon and sulfur from the bulk to the surface. Hydrogen was admitted to remove the carbon and sulfur from the surface by reaction. After this treatment, the crystals were held in vacuum at 800°C for a prolonged period (e.g., 72 hr) to remove hydrogen from the iron.

When this process was complete, the iron crystals were removed from the vacuum tube furnace, repolished, and electropolished. They were then placed into the apparatus for adhesion, LEED, and Auger studies.

The nonferrous crystals were electropolished and the orientations checked before mounting in the adhesion apparatus. Some crystals were mounted in an insulated holder so that they could be ion bombarded.

The vacuum system was evacuated to 10^{-11} torr, and the crystals were ion bombarded for 2 hours after the system pressure was raised to 8.0×10^{-5} torr with argon gas. The ion gun voltage was 250 volts. The crystals were then heated to 250° C for 10 minutes to remove trapped argon, and a clean surface was obtained.

Ion bombardment was not effective for the cleaning of all crystals, and the technique for cleaning the surface was dictated by the crystal material. For example, aluminum oxide was removed from the surface by heating the aluminum crystal to 600° C and holding it at that temperature for 72 hours. Earlier studies have shown that the oxygen dissolves into the crystal. This technique is limited in the number of times it can be used by the solubility of oxygen in the metal.

LEED and Auger traces were taken before and after each adhesion experiment to determine changes that had taken place as a result of adhesive contact. Both surfaces were examined where necessary by reversing the materials.

RESULTS AND DISCUSSION

Clean Iron

The iron used in this investigation was triple zone refined and contained less than 10 ppm of sulfur and 8 ppm of carbon, and yet it was very difficult to obtain a clean iron surface. When the iron was heated after ion bombardment, sulfur was found initially on the surface with Auger analysis. Repeated ion bombardment and heating cycles resulted in the elimination of sulfur from the surface. Carbon, however, then became detectable with both Auger and LEED examination of the iron surface.

A LEED pattern for a clean iron (011) surface is presented in figure 2(a). Figure 2(b) is a LEED photograph of that same surface heated to 500° C and held at that temperature for 30 minutes. A ringed structure due to the carbon appears. It was found that an ion bombardment of the surface followed by a minimum in heating to remove effects of bombardment (5 min at 250° C) would result in a clean surface. The LEED pattern was that of figure 2(a), and Auger analysis did not reveal the presence of any carbon.

Adhesion of Lead to Iron

Adhesion experiments were conducted with the face-centered cubic metal lead contacting the clean iron (011) surface. The adhesion forces measured for various applied loads are presented in figure 3. With increasing load, an increase in the force to fracture the adhesive junction is observed. The increase in force to fracture with increasing

load reflects the effect of the increase in true contact area. With the larger applied loads, the real area of contact has increased and with this increase is associated an increase in the number of adhesive bonds developed across the interface.

When a tensile force is applied to the adhesive junction between iron and lead, fracture in the interfacial region is to be expected in the area of weakest bonding. This would exist in the lead to iron bonds or in the cohesive bonds of lead. An Auger trace was made of the iron (011) surface after adhesive contact with lead and the results obtained are presented in figure 4. The Auger analysis indicates a transfer of lead to the iron surface. This indicates that the zone of fracture in tension was in the cohesive lead bonds. The adhesive bonds of lead to iron were stronger than the cohesive lead bonds.

Iron and lead are mutually insoluble (ref. 8). Despite the mutual insolubility, the adhesive bonds developed between the two clean metal surfaces were in excess of 47.0 kilocalories per mole (20×10^4 J/mole), the cohesive bonding energy of the lead (ref. 9).

The bonding of lead to elements with which it is not soluble is not limited to iron in adhesion studies. Estrup and Morrison (ref. 10) found that lead deposited on a silicon surface in a monolayer had an interatomic lead atom to lead atom distance of 3.3 Å (3.3×10^{-10} m). The bond distance in bulk lead is 3.5 Å (3.5×10^{-10} m). The interatomic contraction in the lead is a result of the strong adhesive bonds developed between the lead and silicon. The adhesive bonds between the lead and silicon are stronger than the cohesive lead bonds. These strong bonds exist despite the insolubility of lead in silicon (ref. 8).

Adhesion of Iron to Cobalt and Nickel

Adhesion experiments were conducted with the (0001) surface of cobalt and the (111) surface of nickel contacting the iron (011) surface. Cobalt has the closely packed hexagonal structure and nickel a face-centered cubic structure. The adhesion results obtained together with some other properties of these metals are presented in table I. Both cobalt and nickel have approximately the same cohesive energy and atomic size. They have identical valency states. Cobalt exhibits 35 percent solubility prior to ordering in iron, while nickel has a solubility of 9.5 atomic percent (ref. 8).

Adhesion results indicate a greater bonding force for nickel to iron than for cobalt to iron. The iron surfaces were examined after adhesive contact with LEED and Auger analysis. Cobalt was found to be present on the iron surface, indicating fracture of cobalt cohesive bonds. Nickel was not found on the iron surface. A larger nickel (111) flat was used, and adhesive contact was made to the nickel (111) surface with a 3.0-millimeter-diameter iron (011) surface. The nickel surface was examined with

LEED and Auger after adhesive contact and iron was found to be present on the nickel surface.

An examination of the cohesive energies for iron, cobalt, and nickel in table I indicate that they are nearly the same, yet differences in adhesive forces to iron exist. The cohesive energies do not, however, reflect orientation effects. The values in table I reflect an average of the lattice cohesive energy for each of the metals. The minimum for cohesive energy in cobalt would exist between atoms in adjacent basal planes (ref. 10). This may account for the lower adhesive forces of cobalt to iron than for nickel to iron. The cohesive forces between (0001) planes in cobalt would be less than the forces between (111) planes in nickel.

The outer electron configuration and thus the electrons that would enter into adhesive bonding for these metals are iron $3d^6 4s^2$, cobalt $3d^7 4s^2$, and nickel $3d^8 4s^2$. For these metals it is primarily the 3d and 4s electrons that enter into adhesive bonding (ref. 11). It is these electrons that act as the glue in adhesion and impart the chemical activity to metal surfaces. Since cobalt transferred to iron, it may be assumed that the cohesive bonds in cobalt were weaker than the adhesive iron to cobalt bonds or the iron to iron cohesive bonds. With nickel, however, iron transferred to the nickel surface, which indicated that the iron to iron bonding was the weakest. The adhesive forces of nickel to iron were less than the forces of iron to itself. Since iron cohesive bonding is involved for both couples, the differences in adhesive forces must be the result of atomic packing, size factor, and lattice spacing at the interface, all of which would affect the amount of metal involved in interfacial bonding.

With respect to solubility, cobalt has greater solubility in iron than nickel (see table I). If solid solubility influences adhesion, it would be anticipated that cobalt and not nickel would exhibit the higher adhesive forces to iron. The Hume-Rothery rules are more closely met with nickel (ref. 12). Yet, the data indicate just the opposite.

Adhesion of Noble Metals to Iron

Copper, silver, and gold were brought into adhesive contact with the (011) surface of iron. The noble metal plane contacting the iron was the (111). Adhesion results obtained are presented in table I. Copper, the most chemically active of the noble metals, exhibited greater than twice the adhesive force to iron than did the other two metals.

While all three noble metals are hyperelectronic (excess of electrons), as indicated by the data of table II, and should develop strong bonds with either hypoelectronic (electron deficient) or buffer elements, there is a difference in the degree of interaction or chemical activity with iron. Copper in table I exists in valency states of both 1 and 2, the latter being the more common while silver and gold exist primarily in a valency state of 1.

Copper, silver, and gold all transferred to a clean iron (011) surface. Figure 5 is an Auger spectrometer trace showing the presence of gold on the iron surface. All three noble metals have lower cohesive energies than iron and if metal transfer occurs, transfer of the noble metal to iron would be expected. Again, the adhesive bonds at the interface were stronger than the cohesive bonds in the weaker of the two metals.

The solubility of all three noble metals in iron is relatively low, as indicated in table I. Despite the very limited solubility of these elements in iron, their adherence to a clean iron surface was very strong. It varied from $2\frac{1}{2}$ times the applied normal load for gold to $6\frac{1}{2}$ times the applied load for copper.

Figure 6 presents LEED patterns for the iron (011) surface after adhesive contact with the noble metals. The structural arrangement of the noble metal on the iron surface after fracture of adhesive contact is essentially the same. This may be related to the similarity in electronic structure.

Adhesion of Platinum to Iron

A platinum (111) surface was brought into adhesive contact with the iron (011) surface, and the adhesion forces measured are presented in table I. While having a relatively good solubility in iron, the adhesive force measured was appreciably less than that measured for nickel, where the solubility is less than half of that of platinum in iron. Platinum, however, is not as chemically active as is nickel.

Adhesion of Aluminum to Iron

The very chemically active metal aluminum was brought into adhesive contact with iron, the (111) surface of aluminum contacting the (011) surface of iron. The adhesive forces measured were very large, as indicated by the data of table I. The force of adhesion was $12\frac{1}{2}$ times the applied load. The forces of adhesion measured between iron and aluminum were greater than those between iron and any other metal examined in table I with the exception of iron itself. Aluminum is a hypoelectronic element, as indicated by table II, and strong interaction of hypoelectronic elements with iron might be expected.

The cohesive energy for aluminum in table I indicates that it is in the same general range as copper and silver and, consequently, the contact area with deformation under load might not be too greatly different. This is particularly true since all three are face-centered cubic metals with the same surface orientation. The adhesion values are, however, markedly different. The adhesive forces of aluminum to iron were greater

than four times the value for silver and nearly twice the value observed for copper. The difference in these three face-centered cubic metals is the chemical reactivity of the surfaces. Aluminum is more reactive than copper, which in turn is more reactive than silver. This is reflected in the valency states of these metals in table I. Aluminum has a normal valency state of 3, copper 1 and 2, and silver normally 1.

The solubility of aluminum in iron is 22 atomic percent. The solubility of platinum in iron is 20 atomic percent. Despite this similarity of solubility in iron, the adhesive forces of aluminum to iron were $2\frac{1}{2}$ times the adhesive force of platinum to iron. The differences in cohesive energies for the two metals would indicate a greater contact area for aluminum than for platinum. It is of interest to note that, even where aluminum is insoluble in an element, surface interactions can take place with stable bonding. Lander and Morrison have shown the formation of ordered phase surface structures as a result of bonding of aluminum to silicon (ref. 13). This structure forms despite the fact that the aluminum is insoluble in silicon (ref. 8). This again argues against the use of bulk properties for the prediction of surface behavior.

Adhesion of Tantalum and Oxidized Tantalum to Iron

A tantalum (011) surface was brought into adhesive contact with the clean iron (011) surface. The adhesion force measured for an applied load of 20 dynes (20×10^{-5} N) was 230 dynes (230×10^{-5} N). Tantalum, much like aluminum, exhibited strong bond forces to iron (see table I). Tantalum, like aluminum, is hypoelectronic (table II) and should develop strong bonds with iron. The cohesive energy of tantalum is very high, indicating that with loading, the iron rather than the tantalum may be undergoing deformation.

The force of adhesion of tantalum to iron was measured as a function of applied load, and the results are presented in figure 7. The force of adhesion increases with increases in load just as it did for lead over the same load range in figure 3. With the cohesively stronger deforming in figure 7, the slope of the curve indicates less sensitivity of the iron-tantalum couple to load than was observed in figure 3 with the iron-lead couple where the cohesively weaker lead was deforming.

Adhesion studies were also conducted with some of the metals present in table I with oxygen present on their surfaces. These metals with oxygen present on the surface were brought into adhesive contact with clean iron. The object of these studies was to determine what effect oxygen on one surface would have on adhesion and where, if bonding of iron to oxygen took place, adhesive bonds would fracture. LEED and Auger analysis were used on the surfaces before and after adhesive contact.

The force of adhesion of oxygen covered tantalum to clean iron is presented in figure 7 as a function of applied load. The adhesive force measured was markedly less

than was observed for the clean metals in contact. Further, the adhesion force did not continuously increase with applied load as was observed with the clean metals. With clean metals in contact, iron transferred to tantalum. With oxygen present on the tantalum, oxygen transferred to the iron surface.

An Auger trace of the iron surface after adhesive contact with oxidized iron is presented in figure 8. The presence of oxygen in the trace indicates that, with fracture of the adhesive bonds, oxygen transferred from the tantalum to the iron surface. Oxygen to tantalum bond scission had occurred.

Adhesion of Oxygen-Covered Metal Surfaces to Iron

In figure 9 two LEED patterns are presented indicating the presence of oxygen transfer to the iron (011) surface as a result of adhesive contact. Figure 9(a) indicates the presence of oxygen transferred to the iron from a nickel (111) surface. Figure 9(b) indicates the presence of oxygen on the iron surface after adhesive contact with an oxygen-bearing tantalum surface. The LEED pattern of figure 9(b) confirms the Auger detection in figure 8 of oxygen.

Adhesion measurements were made with oxygen-covered copper contacting the clean iron (011) surface, and the results obtained are presented in figure 10 together with data for clean copper contacting iron. At very light loads, the adhesion force was not affected by load. When the applied load exceeded 60 dynes (60×10^{-5} N), the adhesive force began to increase just as it had done for clean metals in contact. At the very light loads, fracture of the adhesive junction resulted in fracture of the copper to oxygen chemical bond since oxygen was found to be present on the iron surface with Auger analysis. When the load was increased to in excess of 60 dynes (60×10^{-5} N), deformation at the interface brought about iron to copper as well as iron to oxygen bonding. Fracture in the surficial layer after adhesive contact resulted in the rupture of copper-oxygen and copper-iron bonds. The shift in the curve for copper with oxygen present in figure 10 to the right of the curve obtained for the metals in the clean state represents the effect of the weaker copper to oxygen bond. The binding energy of the metal which transferred to iron is 81 kilocalories per mole (34×10^4 J/mole), while for the oxide it is only 30 kilocalories per gram atom (13×10^4 J/g atom) of oxygen.

If adhesion experiments are conducted with oxygen-covered metal surfaces contacting clean iron and the load is kept at 20 dynes (20×10^{-5} N), the iron to oxygen bonding will occur primarily and the force to fracture the adhesive junction will be a measure of metal to oxygen bond strength. Such experiments were conducted, and the results obtained are presented in figure 11. The force to fracture the adhesive junction is plotted as a function of the energy to separate the metal from oxygen.

Examination of figure 11 indicates that the force to fracture the adhesive junction is related to the metal to oxygen binding energy. With copper, nickel, cobalt, and tantalum, oxygen was found, by Auger analysis, to have transferred to iron. It was the rupture of the oxygen to metal bond which resulted in the measured adhesive forces of figure 11.

With aluminum, both oxygen and aluminum were found present on the iron surface after adhesive contact. These results indicate that the weakest region in the surficial region on adhesive contact was in the aluminum cohesive bonds. The cohesive binding energy of aluminum to itself is less than the binding energy of aluminum to oxygen. The other metals in figure 11 all have stronger metal to metal than metal to oxygen binding energies.

Supplemental Discussion

It appears from the data presented in this investigation that chemical reactivity of a metal exerts an influence on the adhesion of metals to iron. In an earlier study with the face-centered cubic metal gold contacting copper, an effect of chemical reactivity on adhesion was also noted (ref. 14). With a specimen configuration the same as that used herein for an applied load of 20 dynes (20×10^{-5} N), the force to fracture adhesive bonds between gold and copper (111) surfaces was 80 dynes (80×10^{-5} N). With the addition of 1.0 atomic percent aluminum to the copper, the adhesive force of the gold to the copper increased fivefold to 400 dynes (400×10^{-5} N). The aluminum was present in the copper in solid solution. The aluminum, however, underwent equilibrium segregation to the surface resulting in surface coverages far in excess of the aluminum concentration in the bulk (ref. 15).

On the basis of solid solubility, gold would be expected to have a greater affinity for copper than for aluminum. With copper, gold forms a continuous solid solution with two ordered structures, Cu_3Au and CuAu . Gold has limited solubility in aluminum with the possible formation of at least five compounds. Adhesion measurements indicate markedly stronger bonding of gold to aluminum and aluminum containing copper alloys than to copper.

Examination of table II indicates that both gold and copper are hyperelectronic while aluminum is hypoelectronic. Stronger bonds would be anticipated between a hyperelectronic metal and a hypoelectronic metal than between two hyperelectronic metals (ref. 16).

Since electrons are the glue that holds materials together, both cohesively as well as adhesively, more attention must be focused on the electronic character of solid surfaces and those factors which influence the electronic surface structure. It has already been demonstrated that the atomic planes of metals in contact influence the adhesive forces.

With closely packed structures where electron interaction with like atoms is at a maximum, the energy of any atom available for adhesion is at a minimum. The surface energy of these closely packed planes is at a minimum as is adhesion. Electron theories have been advanced to explain surface energy (ref. 16), and these may be applicable to adhesion.

In this study with various metals contacting clean iron, certainly chemical reactivity of the metal involved was more decisive in the measured adhesive force than was the bulk property of solid solubility. Metals which exhibited very limited or no solubility in iron adhered very readily to a clean iron surface. The resulting adhesive bonds were stronger than cohesive bonds in the metal, and metal was found transferred to the iron surface. The ability of these metals to adhere to iron and the resulting bond strength is a function of the electronic structure on the surface of these metals.

CONCLUSIONS

Based upon the adhesion experiments conducted in this investigation with various metals contacting a clean iron (011) surface and the results of LEED and Auger analysis of these surfaces, the following conclusions are drawn:

1. All of the metals examined in adhesive contact with iron in the clean state adhered strongly to the iron surface. This included metals of limited or no solubility in iron as well as the noble metals.
2. In general, the adhesive bond formed at the interface between the clean metal surfaces was stronger than cohesive bonds in the weaker of the two materials.
3. Chemical reactivity also appears to exert an influence on the measured adhesive bond forces since the more chemically active metals exhibit stronger bonding. For example, with aluminum, copper, and silver, all three metals have comparable cohesive energies (less than iron). All three were observed to transfer to iron. Yet, the adhesive forces measured were greatest with aluminum and least with silver.
4. With oxygen present on the metal surfaces contacting clean iron, fracture of the adhesive junction took place between the metal and oxygen where the metal to oxygen bond was weaker than the cohesive bonds in the metal. The measured adhesive forces to fracture could be related to the metal to oxygen chemical bond energy.

Lewis Research Center,
National Aeronautics and Space Administration,
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TABLE I. - SOME PROPERTIES OF VARIOUS METALS AND FORCE OF

ADHESION OF THESE METALS TO IRON

Metal	Cohesive energy ^a		Atomic size, ^b Å (10 ⁻¹⁰ m)	Valency states ^c	Solubility in iron, ^d at. %	Adhesion force to iron, ^e dynes (10 ⁻⁵ N)
	kcal/g atom	J/g atom				
Iron	99.4	40.5×10 ⁴	2.86	2, 3	-----	>400
Cobalt	101.7	42.6	2.50	2, 3	35	120
Nickel	102.3	42.9	2.49	2, 3	9.5	160
Copper	80.8	33.8	2.551	1, 2	<.25	130
Silver	68.3	28.6	2.883	1	.13	60
Gold	87.6	36.6	2.877	1	<1.5	50
Platinum	134.8	56.4	2.769	2, 4	20	100
Aluminum	76.9	32.3	2.80	3	22	250
Lead	47.0	19.7	3.494	2, 4	INS.	140
Tantalum	186.7	78.1	2.94	5	.20	230

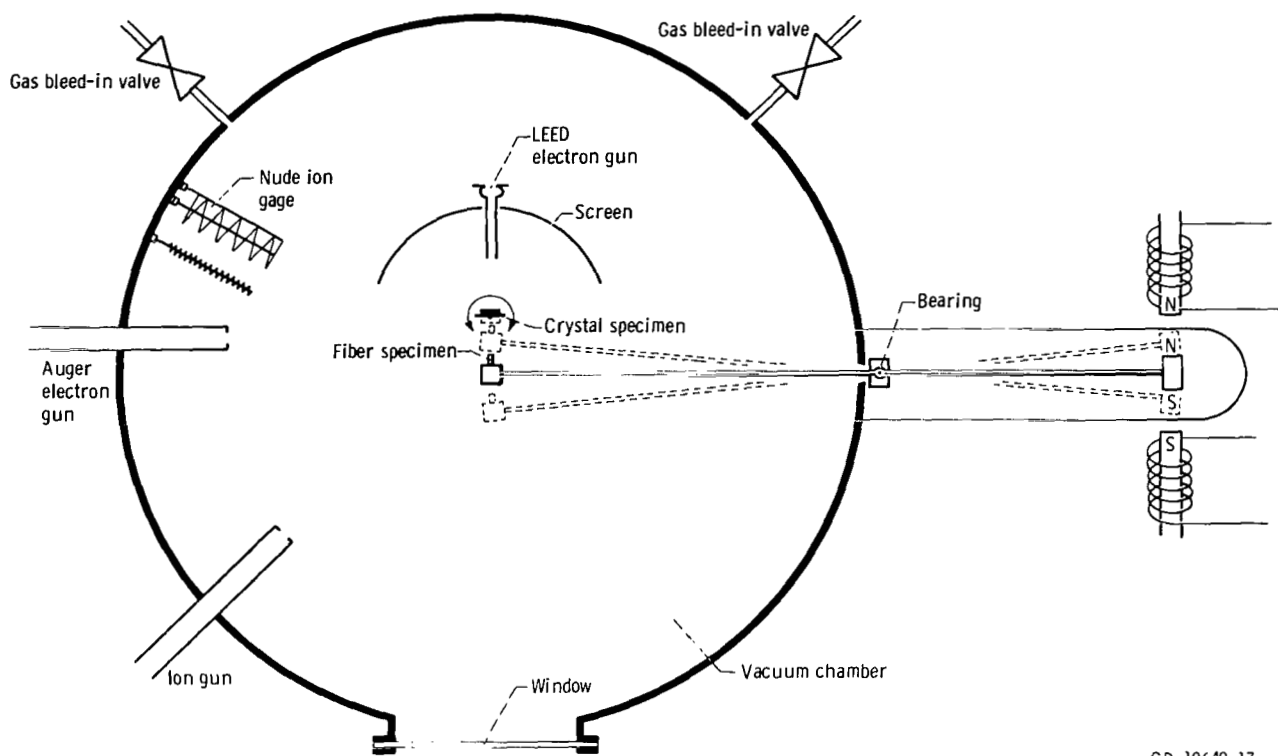
^aRef. 15.^bRef. 16.^cRef. 17.^dRef. 8 and without ordering or introduction of other structures.^eApplied load, 20 dynes (20×10⁻⁵ N); temperature, 20° C; ambient pressure, 10⁻¹⁰ torr.

TABLE II. - ELECTRONIC NATURE OF

VARIOUS ELEMENTS^a

Hypoelectronic elements	Buffer atoms (stable valence)	Hyperelectronic elements
Tantalum	Iron	Copper
Aluminum	Cobalt	Silver
Magnesium	Nickel	Gold
Titanium	Platinum	Oxygen
		Sulfur
		Chlorine
		Fluorine

^aData from ref. 16.



CD-10640-17

Figure 1. - Low-energy electron-diffraction (LEED) adhesion apparatus.

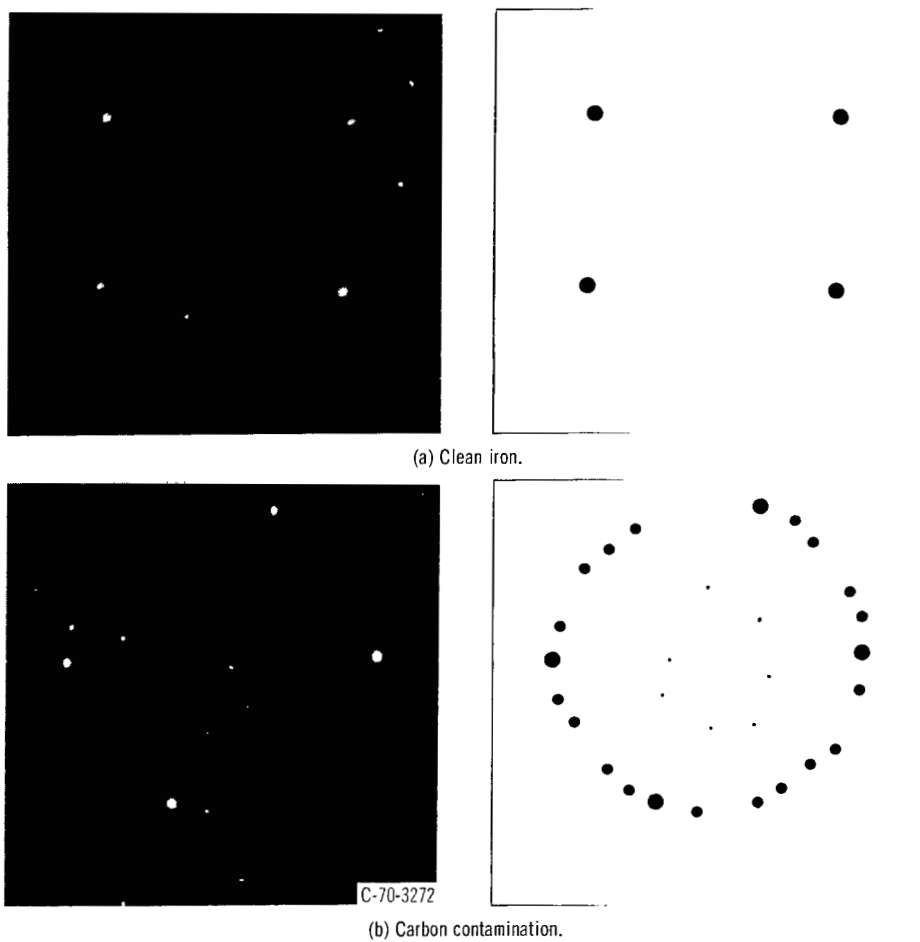


Figure 2. - LEED photographs of a clean and carbon-contaminated iron (011) surface.

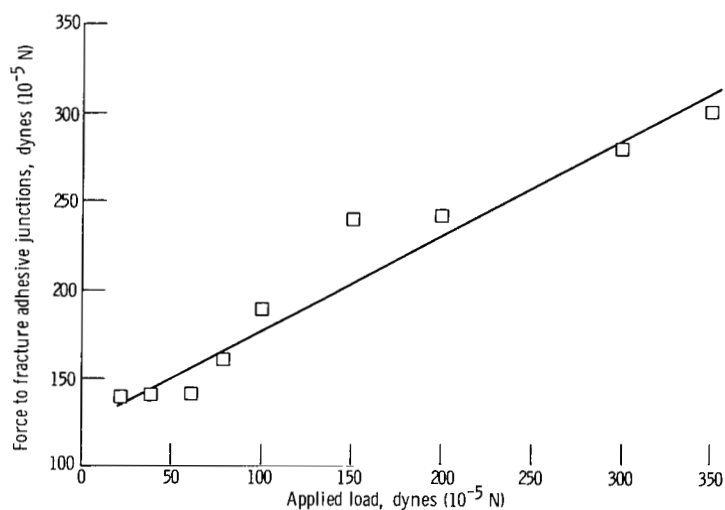


Figure 3. - Adhesion of lead crystal to clean iron (011) surface. Ambient pressure, 10^{-10} torr at 20° C.

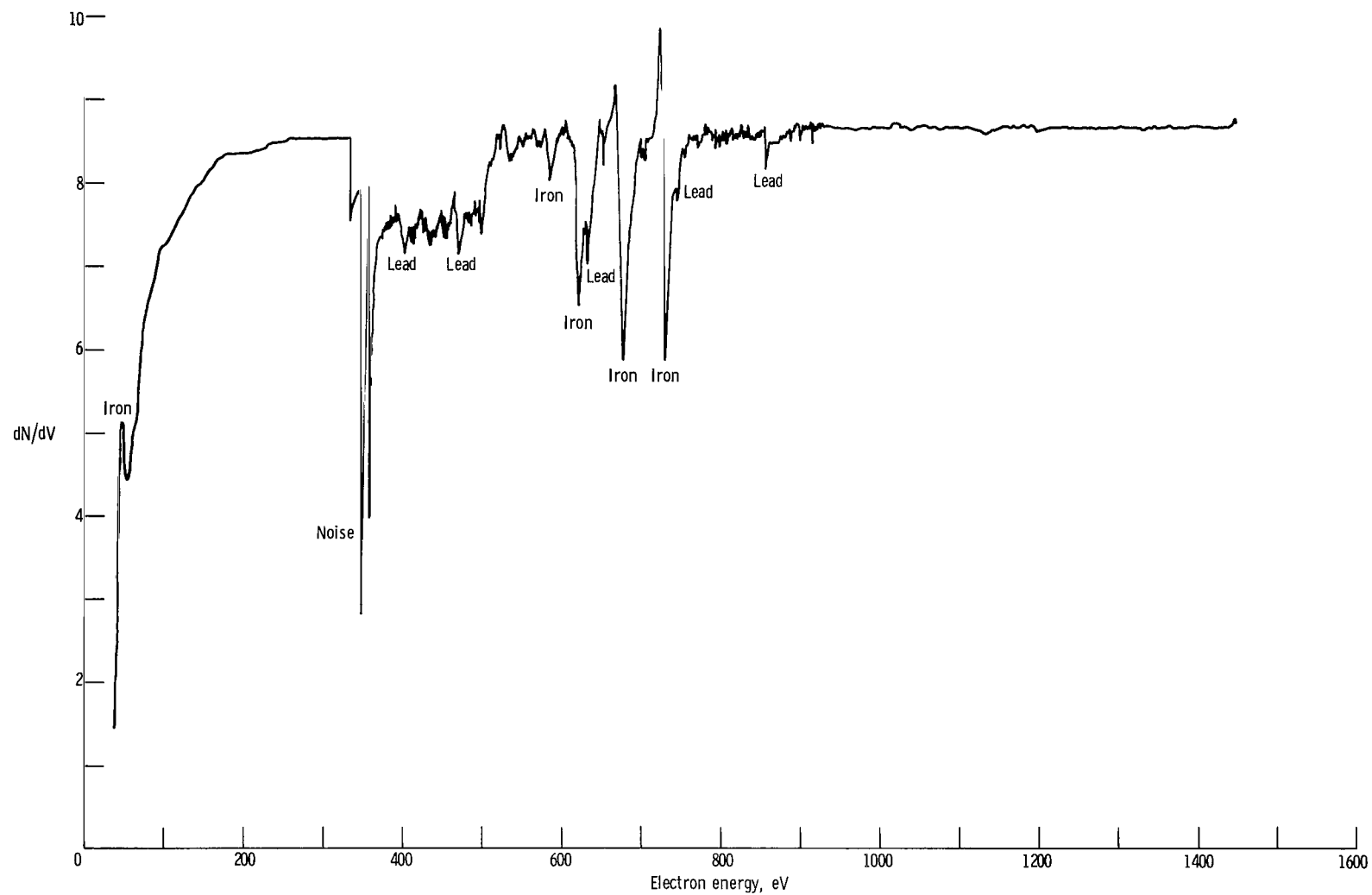


Figure 4. - Auger emission spectrometer trace of iron (011) surface with adhered lead.

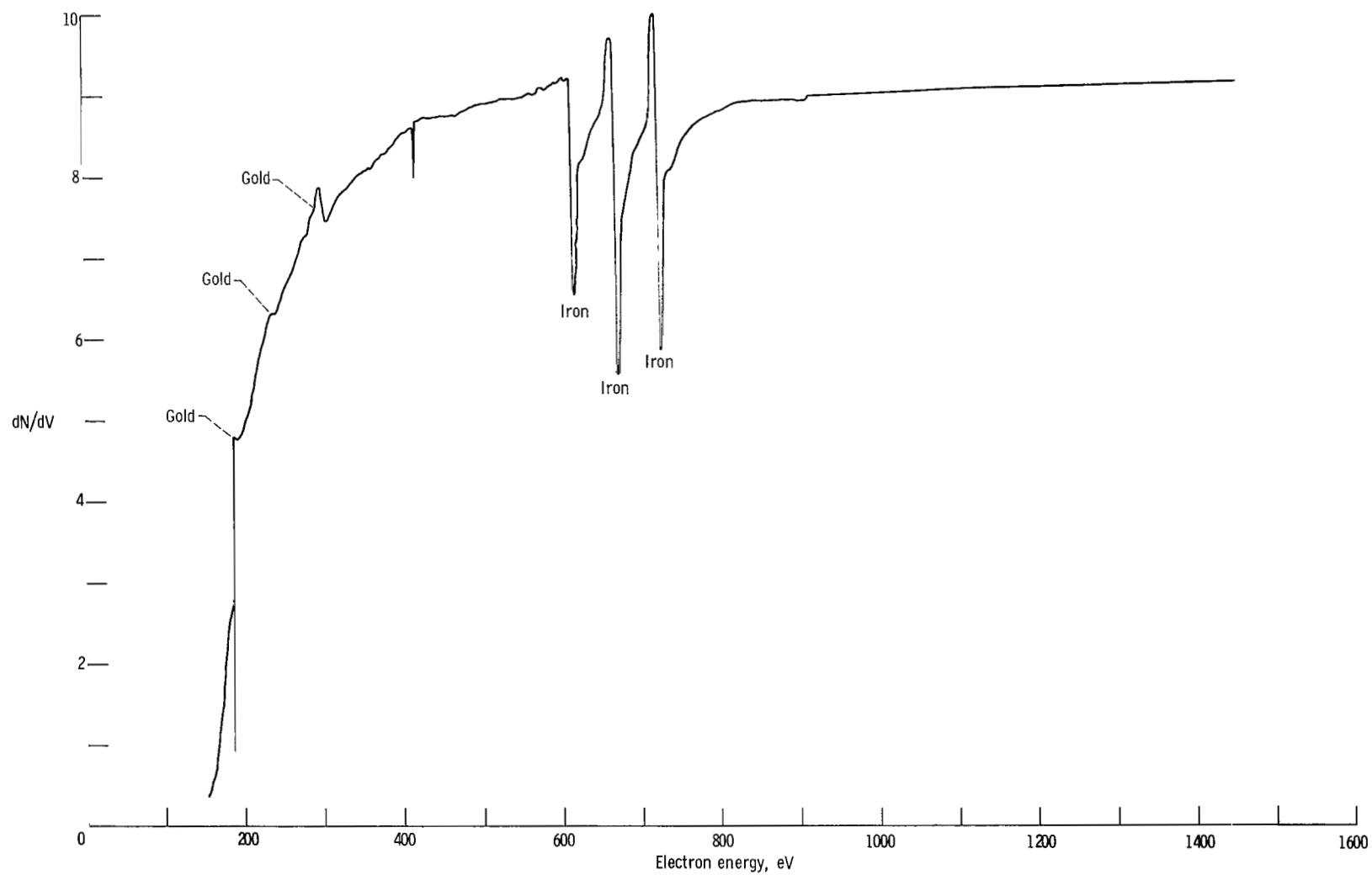
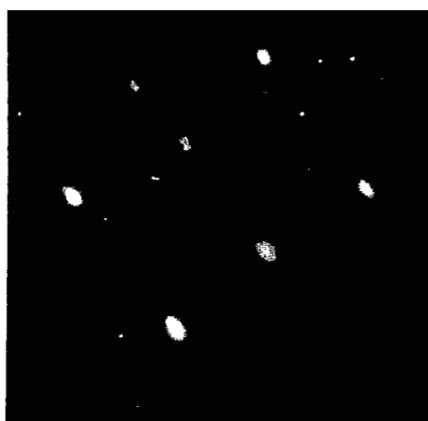


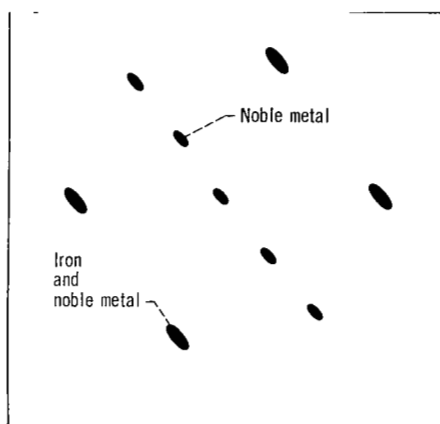
Figure 5. - Auger emission spectrometer trace of iron (011) surface with adhered gold.



(a) Silver.



(b) Copper.



(c) Gold.

Figure 6. - LEED photographs of iron (011) surface after adhesion to noble metals.

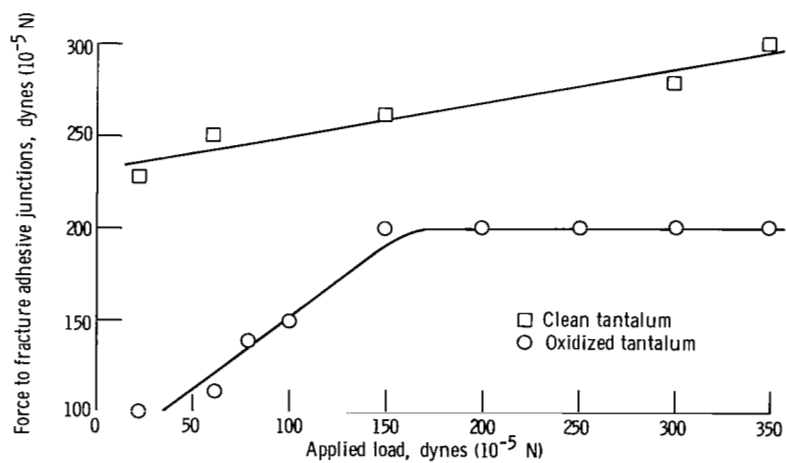


Figure 7. - Adhesion of clean and oxidized tantalum crystals to clean iron (011) surface. Experiments conducted in vacuum of 10^{-10} torr at 20° C.

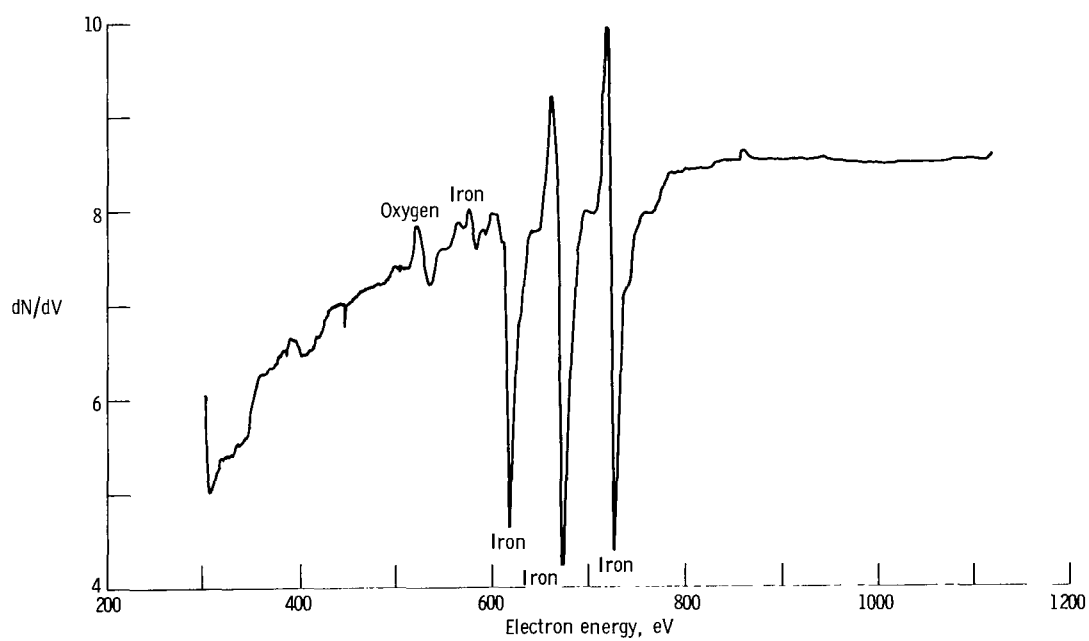
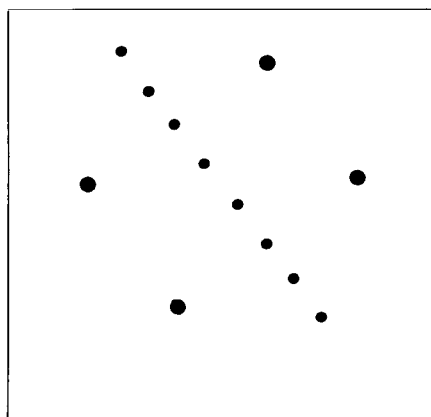
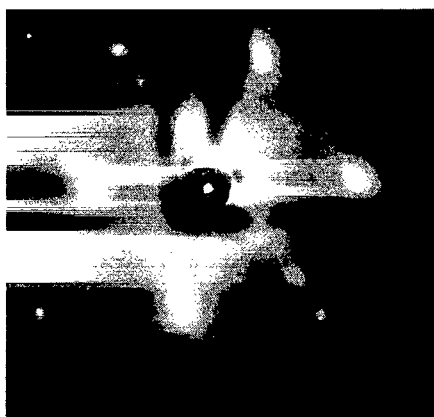
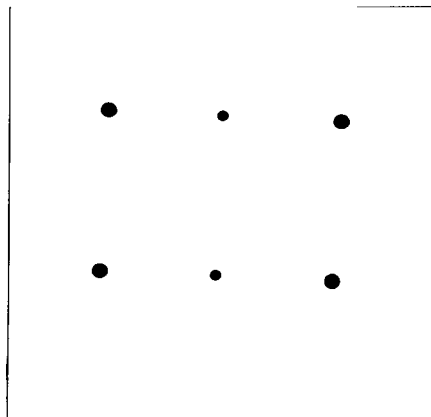
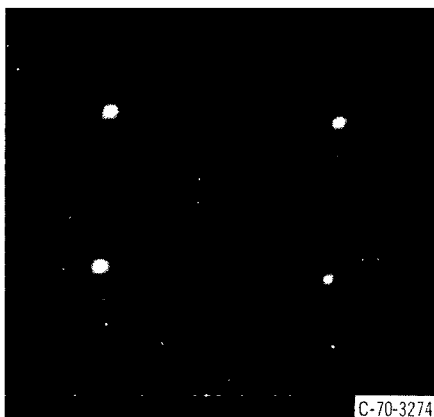


Figure 8. - Auger emission spectrometer trace of iron (011) surface with transferred oxygen.



(a) Nickel with oxide present.



(b) Tantalum with oxide present.

Figure 9. - LEED photographs of iron (011) surface after adhesive contact with nickel and tantalum.

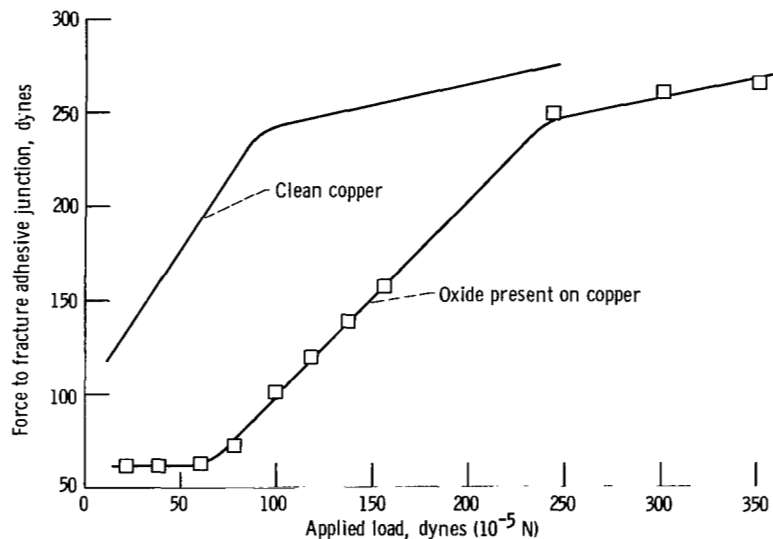


Figure 10. - Adhesion of clean and oxidized copper crystals to iron (011) surface. Experiments conducted in vacuum of 10^{-10} torr at 20° C.

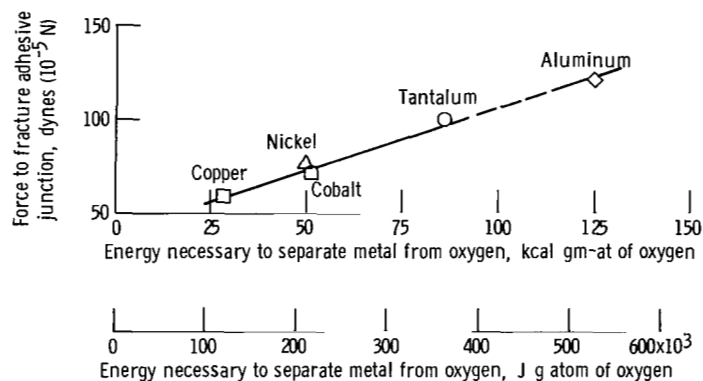


Figure 11. - Force to fracture oxidized metal surfaces from clean iron (011) surface. Applied load, 20 dynes (20×10^{-5} N); temperature, 20° C; ambient pressure, 10^{-10} torr.

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